Simulations of EUV Sources Driven by CO_2 and Thulium Lasers

2019 EUVS Workshop

ARCNL, Amsterdam

Steven Langer, Craig Siders, Tom Galvin,
Howard Scott, Emily Sistrunk Link

November 4th, 2019

LLNL-CONF-795656
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

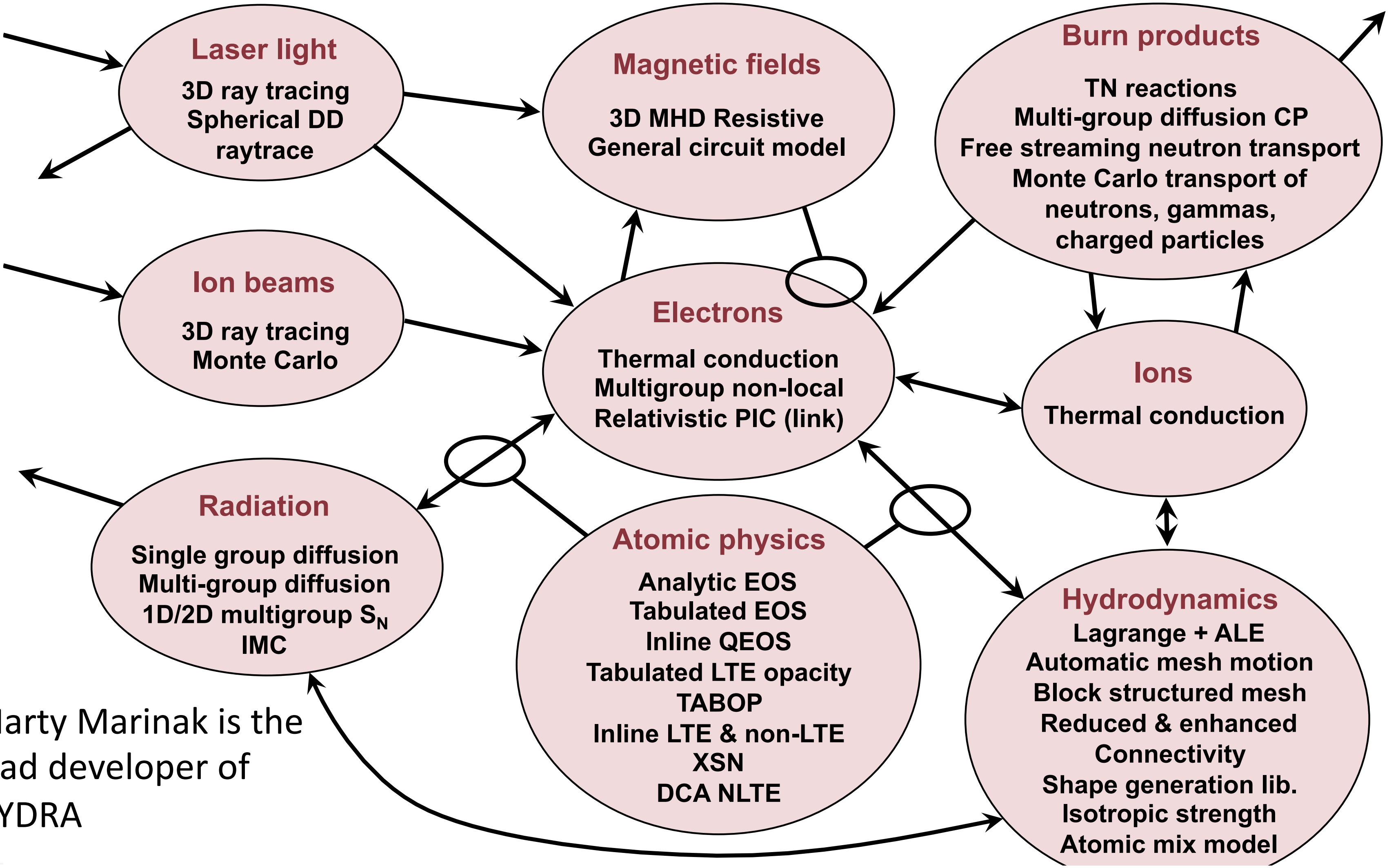
Lawrence Livermore National Laboratory

HYDRA simulations can efficiently explore the utility of different lasers for EUVL sources

- Current laser driven EUVL sources use a CO_2 laser to heat a tin target.
- Other lasers can also drive tin into the temperature and density range where strong 13.5 nm emission occurs.
- Building a new laser and experimentally optimizing its performance is a slow and expensive process.
- Computer simulations can be used to quickly find promising laser designs and reject designs that are unlikely to be efficient at producing 13.5 nm light.
- This study uses HYDRA to simulate EUV sources. HYDRA previously simulated CO_2 laser driven sources under a cooperative R&D agreement with Cymer/ASML[1].
- HYDRA can also simulate EUV source wavelengths shorter than 13.5 nm so it could be used for Blue-X.

[1] Purvis et al. In Proceedings Volume 9776, Extreme Ultraviolet (EUV) Lithography VII. SPIE, Mar. 2016.

HYDRA has physics packages to simulate laser-heated plasmas and was validated against NIF experiments



Laser light
3D ray tracing
Spherical DD
raytrace

Magnetic fields
3D MHD Resistive
General circuit model

Burn products
TN reactions
Multi-group diffusion CP
Free streaming neutron transport
Monte Carlo transport of
neutrons, gammas,
charged particles

Ion beams
3D ray tracing
Monte Carlo

Electrons
Thermal conduction
Multigroup non-local
Relativistic PIC (link)

Ions
Thermal conduction

Radiation
Single group diffusion
Multi-group diffusion
1D/2D multigroup S_N
IMC

Atomic physics
Analytic EOS
Tabulated EOS
Inline QEOS
Tabulated LTE opacity
TABOP
Inline LTE & non-LTE
XSN
DCA NLTE

Hydrodynamics
Lagrange + ALE
Automatic mesh motion
Block structured mesh
Reduced & enhanced
Connectivity
Shape generation lib.
Isotropic strength
Atomic mix model

Marty Marinak is the lead developer of HYDRA

HYDRA simulations in *this* study used the following physics packages

- Laser ray trace
- Inline detailed configuration accounting NLTE opacity calculation
- Tabular equation of state – “best” LLNL EOS for LTE tin
- Both electron and ion heat conduction
- Separate electron and ion temperatures
- Implicit Monte Carlo radiation transport with 65 photon energy groups
- 1D Lagrangian hydrodynamics with roughly 500 zones

The atomic model used in HYDRA calculations has moderate detail

- Atomic data came from FAC (Flexible Atomic Code)
  - configuration-averaged with some configuration interaction corrections
  - a small set of transitions were corrected to better match experiment

- The data was averaged further to decrease the computational cost of inline NLTE

- Atomic kinetics provides a consistent NLTE EOS (to be used soon)

- Goals of the rad-hydro simulations
  - correct energetics + flow of material and radiation
  - approximate (coarsely averaged) radiation spectrum
    - detailed spectra can be generated by post-processing with increased fidelity (and slower running) atomic models, as appropriate

The need for NLTE effects in simulations

- Early simulations of laser heated tin disks showed NLTE effects to be important
- Thickness of the tin targets is small enough that a high fraction of EUV emission escapes
  - low radiation density -> low radiative excitation rate
- At densities characteristic of laser absorption
  - radiative de-excitation dominates collisional de-excitation
    - -> fewer excited electrons **->** lower radiative loss rates than in LTE
- The EUV emission shifts to higher temperatures in NLTE

Laser absorption

- *Most of the laser energy is absorbed* by the plasma:
  - Experiment measured EUV & DUV are a large fraction of the laser energy
- *Inverse bremsstrahlung (IB) absorption of the laser light is weaker than in LTE*
  - Consequence of higher temperature in the NLTE simulations
- *In simulations, IB absorption is augmented*
  - Near critical density, resonance absorption of the laser light is increased to better match the correct (experimental data) total laser absorption

Ensemble simulations are used to study how EUV emission depends on target and laser parameters

- Running an ensemble that spans a range in a multi-dimensional parameter space can identify the parameters (“sweet spots”) that optimize EUV source performance.

- The number of simulations required to investigate a 2D parameter space is ~1000.

- It is highly impractical to run more than ~100 simulations
  - LLNL *Merlin* workflow manager used to automate ensemble runs.

Merlin enables running large ensembles without massive amounts of bookkeeping

- Merlin's automation of ensemble running allows a scientist to focus on understanding the physics of EUV generation:

- Starting from a user supplied HYDRA input deck,
  - Merlin substitutes parameters to be sampled across specified ranges into input decks for each of 1000's of unique runs
  - Merlin submits the ensemble of HYDRA simulations for execution, monitors progress, and finally post-processes each run
  - Merlin generates EUV spectra and conversion efficiencies (CE's) across the ensemble trade space

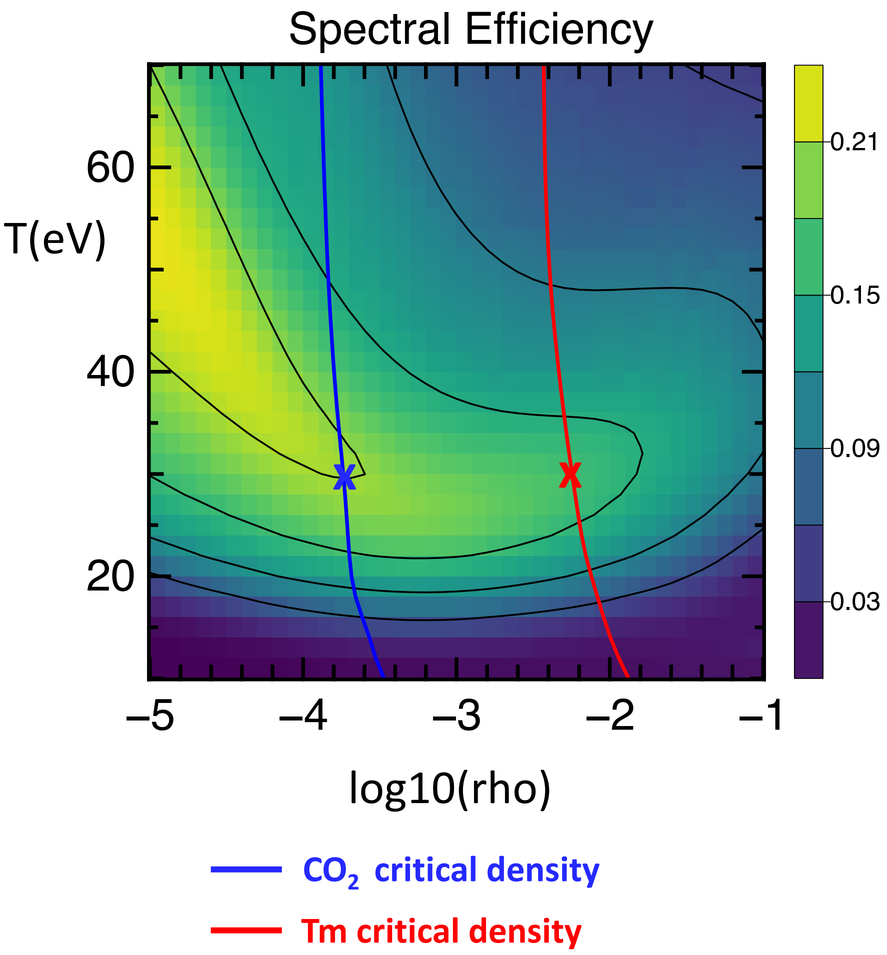
We demonstrate here the capabilities of HYDRA and Merlin by *using simple tin targets*

- Target configurations:
  - A cylinder of uniform density tin vapor
  - or a thin disk of liquid tin
- The laser is incident upon (and heats) one face of the target
- The simulations ignore variations transverse to the laser direction
- A 1000 simulation ensemble can be completed in a day on 32 nodes

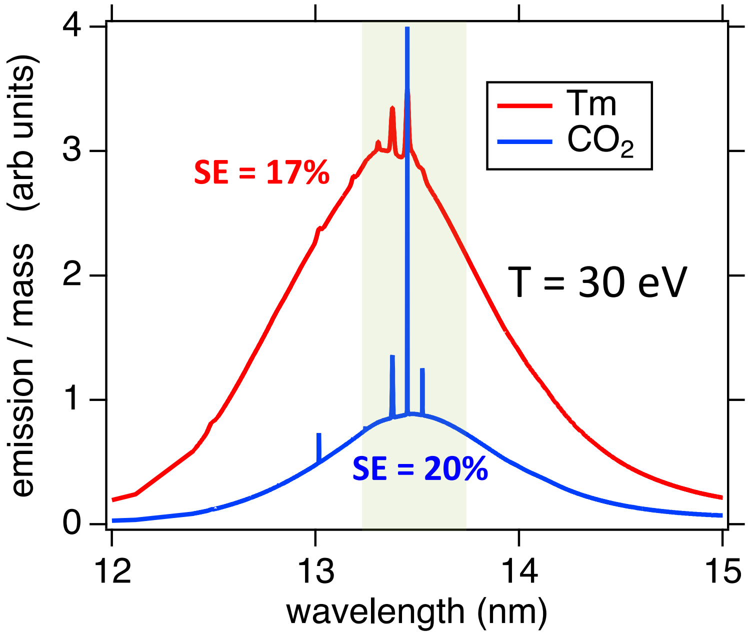
We demonstrate here the capabilities of HYDRA and Merlin by *studying Tm vs CO_2 lasers*

- The thulium “BAT” laser design (Siders et al. Wed.) has several potential advantages
  - Scalable to higher average power, with greater pulse-to-pulse stability than current CO_2 lasers
  - Excellent pulse shaping capability
  - Excellent wall plug efficiency
- The 1.9 μm thulium laser has a critical density ~30 times greater than than of a 10.6 μm CO_2 laser.
- The fraction of tin emission in the 2% bandpass about 13.5 nm is higher at low densities, *all else being equal*.
- Can a thulium laser deliver high EUV CE like a CO_2 laser?

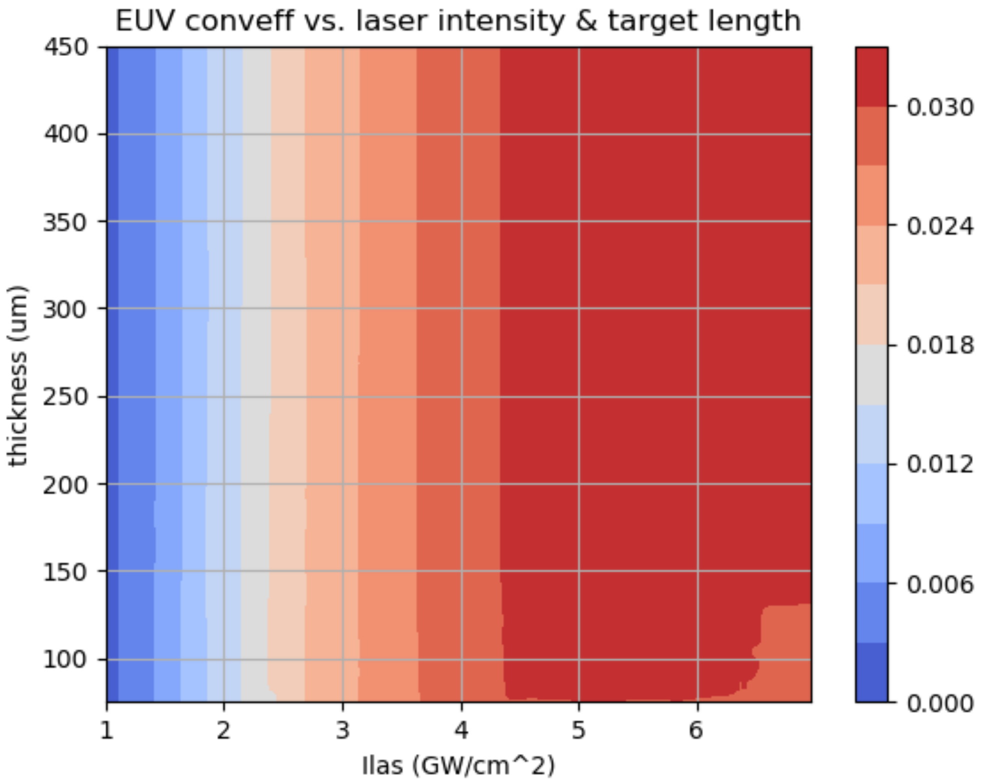
Performance at different laser wavelengths involves tradeoffs in the underlying physics



- Spectral Efficiency (SE: fraction of tin emission in the bandpass) is *greater* at low densities.
- Emission per unit mass is *lower* at low densities.
- Low densities require timescales >100 ns.
- We use simulations to evaluate the tradeoffs.



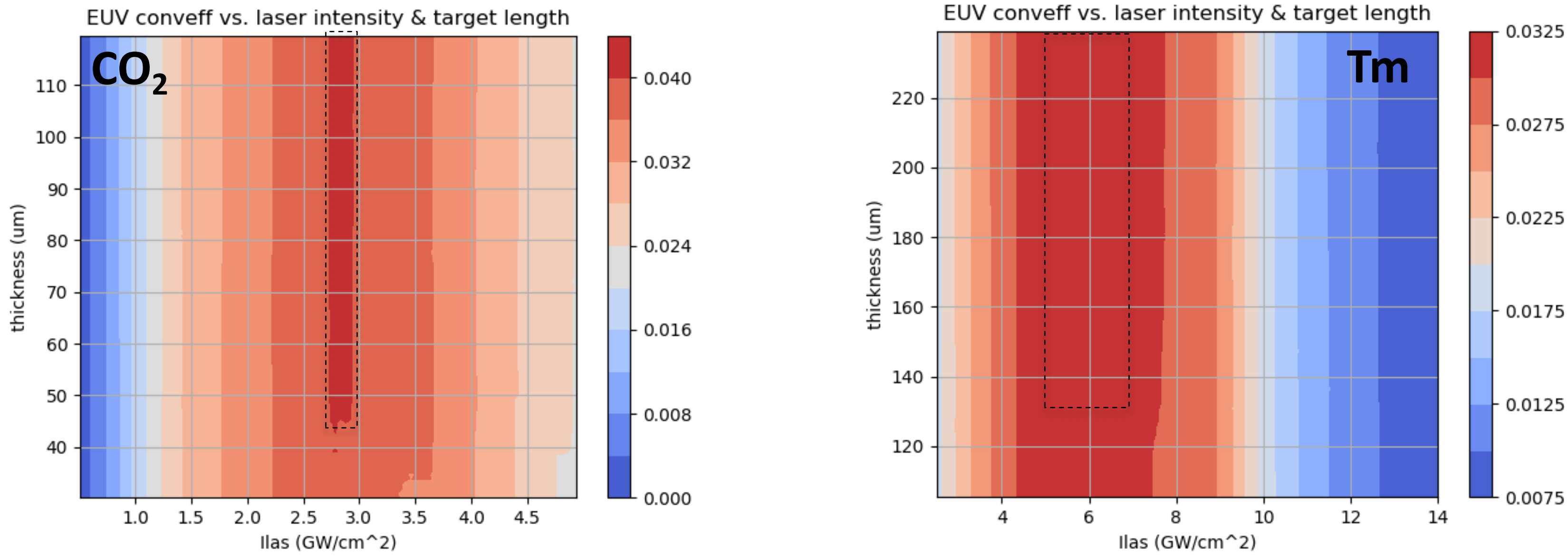
Example ensemble: tin vapor targets (0.04 g/cm^3), 2-um Tm laser



- 365 simulations in ensemble
- 3.3% highest CE in ensemble
- The laser intensity should be ~5 GW/cm^2
- thickness should be >150 μm.
- The density was 0.04 g/cm^3.

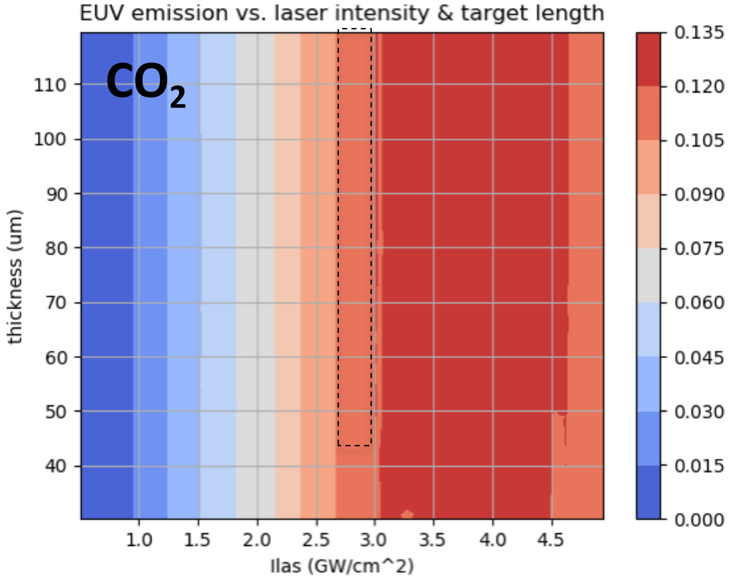
Note: 1D HYDRA-predicted absolute efficiencies are lower than experimental. More experimental pinning required to correct absorbed laser energy. Relative comparisons are more valid.

For tin vapor targets, the CO_2 ensemble shows a *higher* maximum CE than the thulium ensemble, but at a *lower* optimum intensity

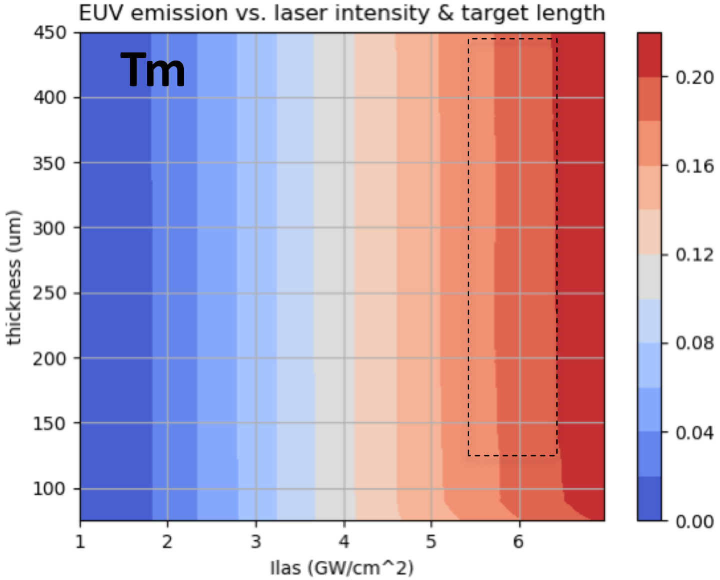


- The CO_2 heated tin vapor target (left) had a peak CE of 4.4% while the Tm heated target (right) had a peak CE of 3.25%.
- The best laser intensity for thulium is *higher* than for CO_2.

The Tm ensemble has a higher EUV exposure (CE x Intensity) than the CO_2 ensemble *at the best CE*



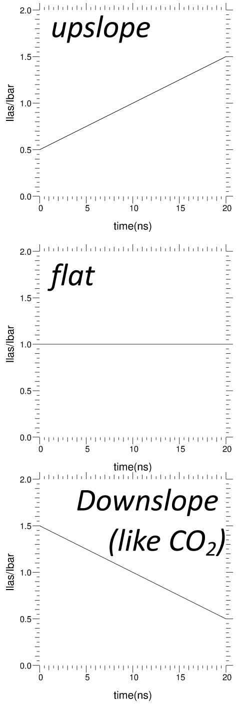
CO_2 tin vapor

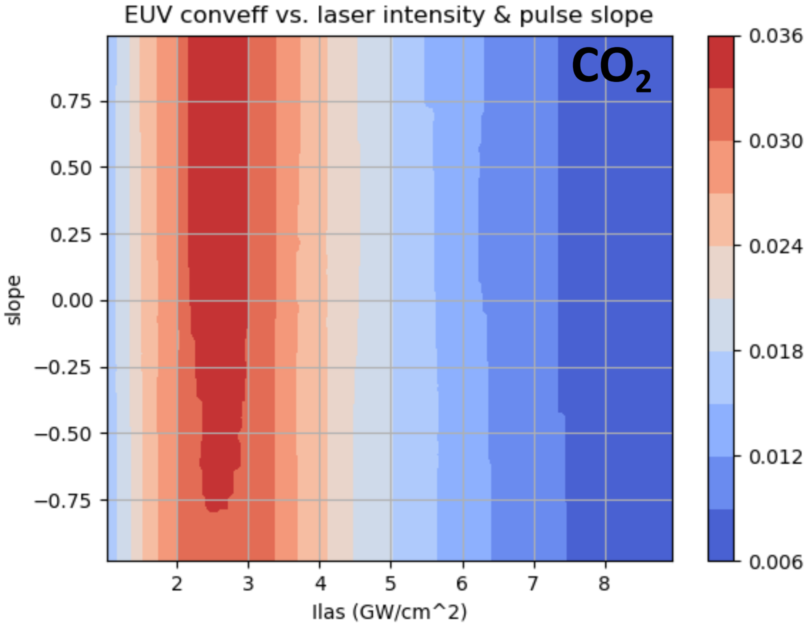


Tm tin vapor

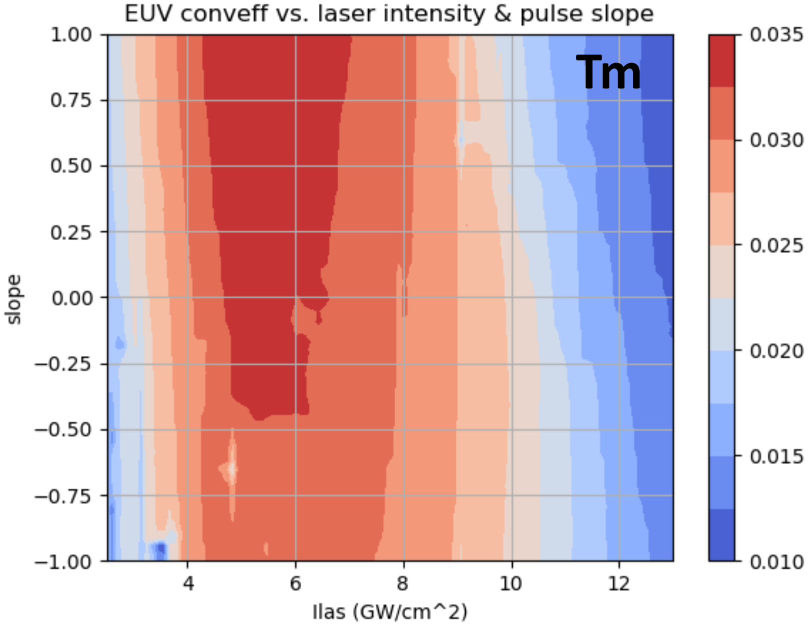
- Operating at high CE reduces the amount of tin injected into the chamber per unit of output EUV.
- The Tm run has a ~50% higher EUV exposure than the CO_2 run *when at their respective peak CEs*.

The laser pulse shape has an impact on CE for Tm and CO_2 heated tin **disk** targets.





CO_2 driven Sn disk

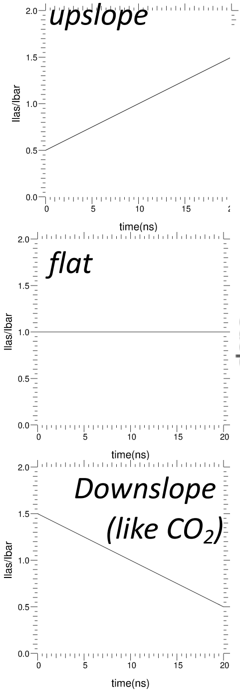


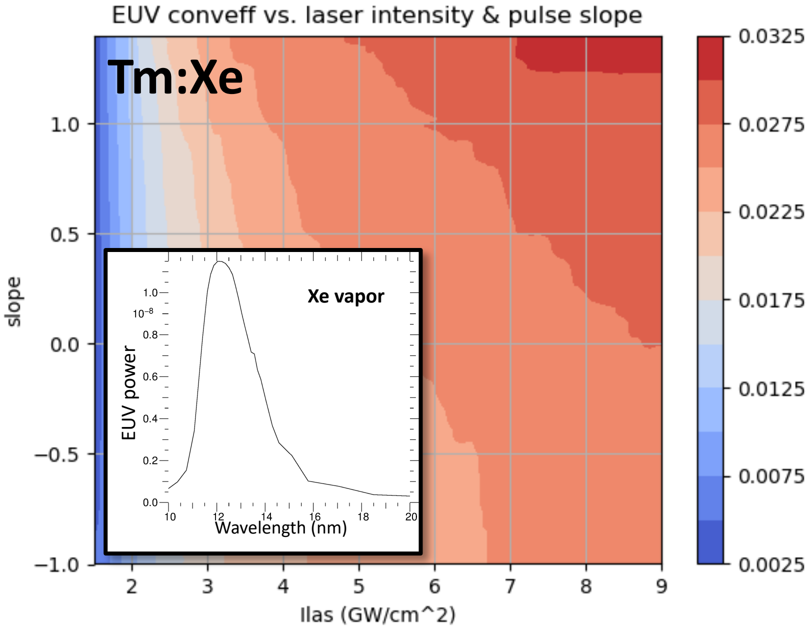
Tm driven Sn disk

- Sample 18 ns pulse shapes are shown at the left. The CE is higher when the laser intensity starts out low and peaks at the end of the pulse. The total laser energy is the same for all runs with the same I_{las}.

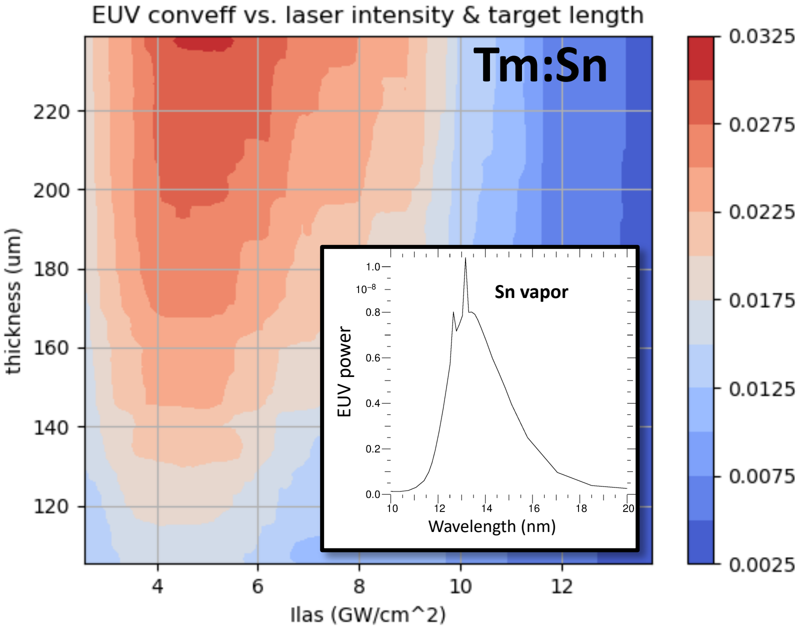
- The maximum CE is about 3.5% for TM and CO_2 driven targets.

An initial Tm ensemble using Xe vapor targets has the same 3.25% CE as tin vapor





Tm driven Xe vapor

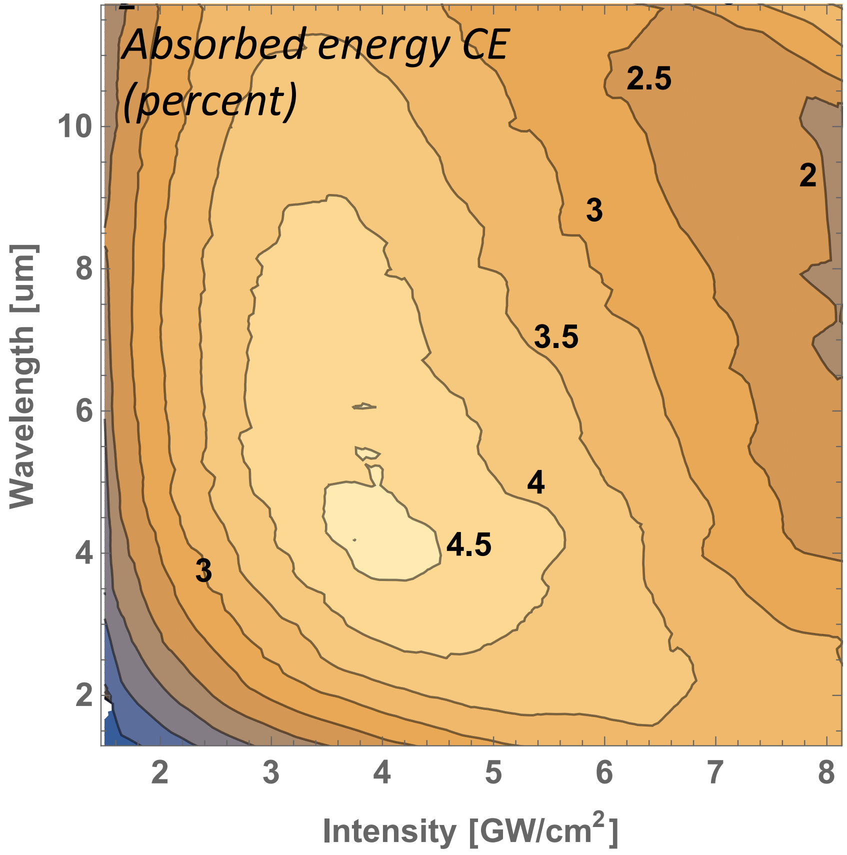


Tm driven Sn vapor

- Extending Xe ensemble to higher laser intensities.
- The peak for xenon is at ~12.2 nm: refinements to the Xe atomic model to include configuration interaction will shift spectrum and introduce narrow lines like Sn

Tm:Sn vapor ensembles over laser wavelength and intensity

1D HYDRA: Sn vapor target



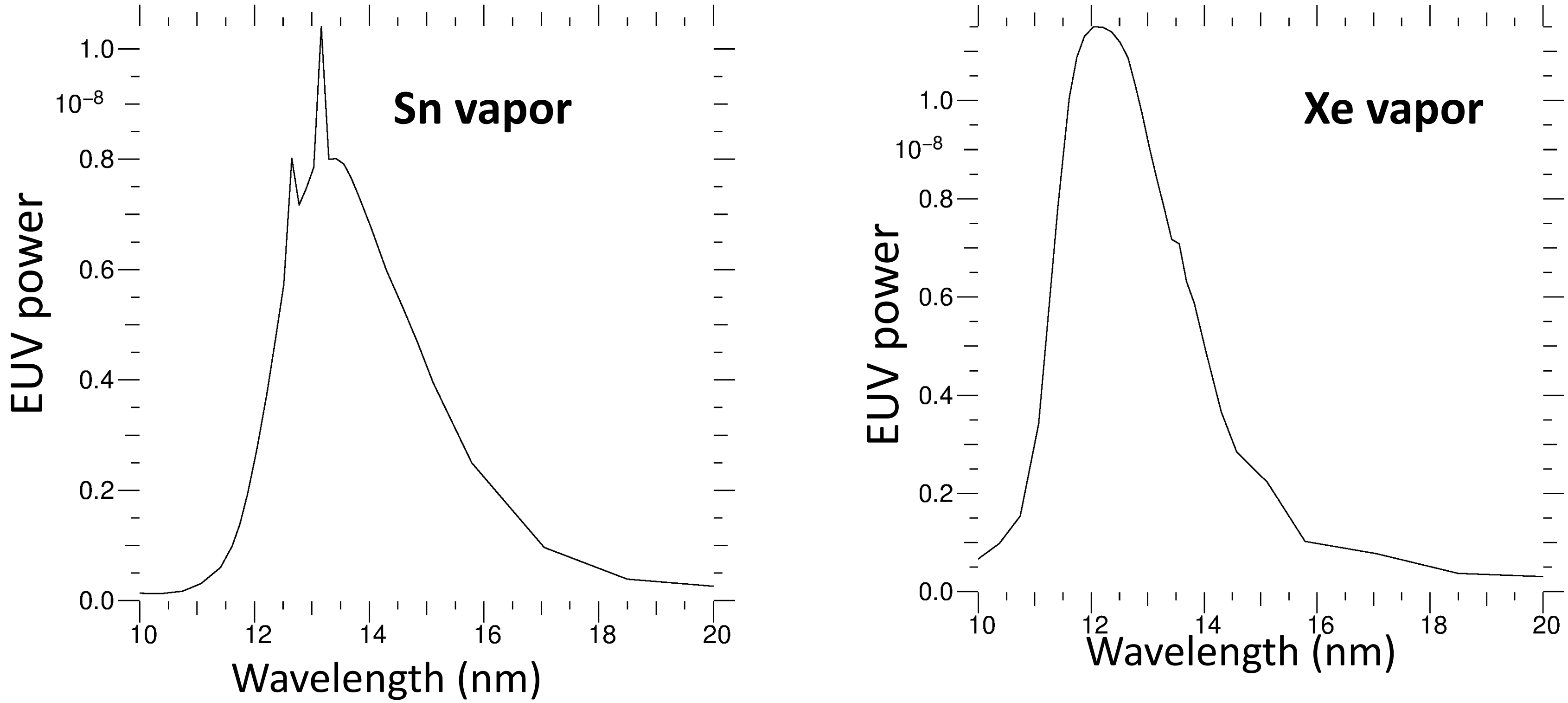
- HYDRA can simulate **any** laser wavelength
- Is there an optimum wavelength
  - For EUV CE?
  - For laser wall-plug electric to EUV CE?
  - For wall-plug electricy to EUV power?
  - For EUV/μg-Sn?
- See *Siders et al*, Wednesday!

A vision for future EUVL source development

- A campaign to develop a new EUVL source starts with candidate lasers and targets.
- Simulations quickly optimize the performance of the candidates. Candidates are adjusted based on simulation results. The process requires no hardware.
- Test facilities are built for the winning candidate(s).
- Simulations are used to help understand departures from the predicted performance and steer experiments towards better performance.
- A production source is designed and built.

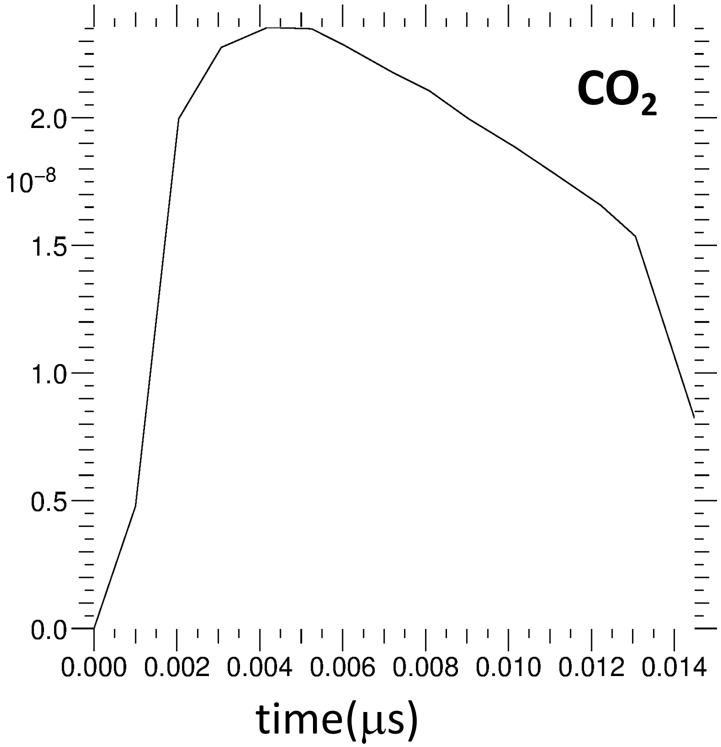
This process would be faster and less expensive than a purely experimental approach.

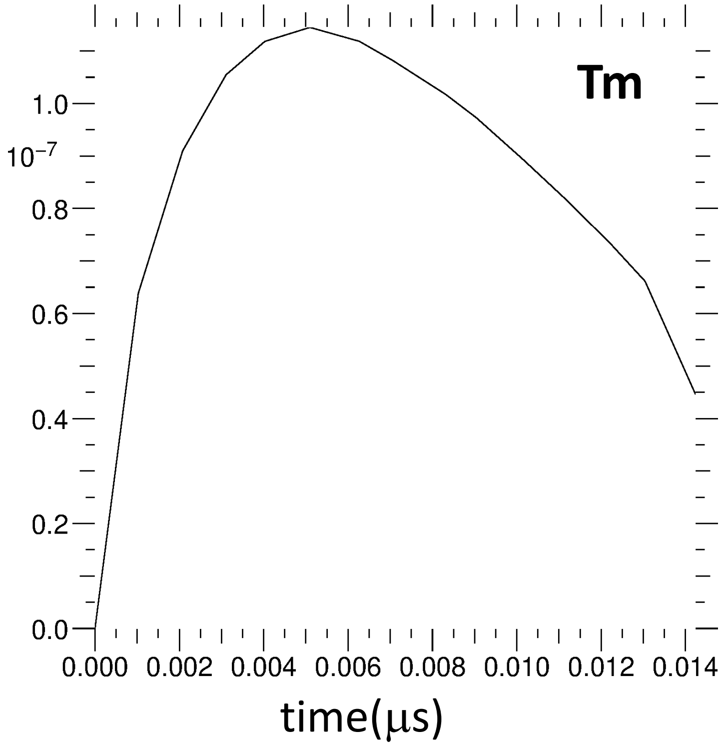
Sn and Xe vapor target spectra demonstrate the impact of atomic models. The Xe model needs to be improved.



- The peak of the tin spectrum is at ~13.2 nm while the peak for xenon is at ~12.2 nm.
- The Xe atomic model was not adjusted for configuration interaction so it does not have a sharp EUV line.

The time dependence of the 13.5 nm emission differs modestly between Tm and CO_2 driven tin disks.

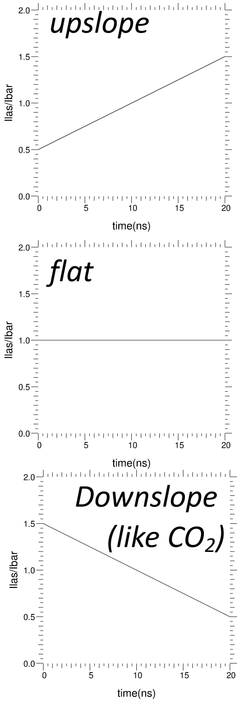


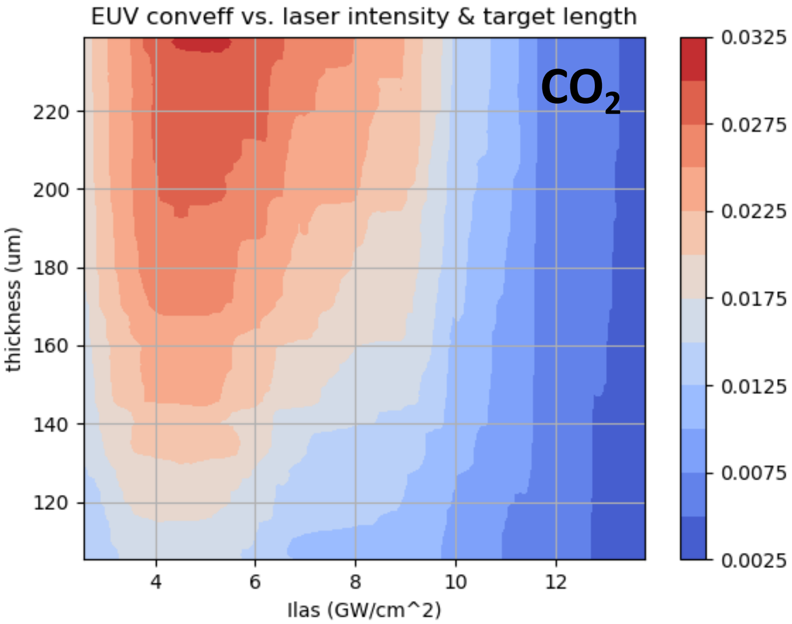


- The 13.5 nm EUV emission peaks at ~ 5 ns for both Tm and CO_2 and the rise time is similar.

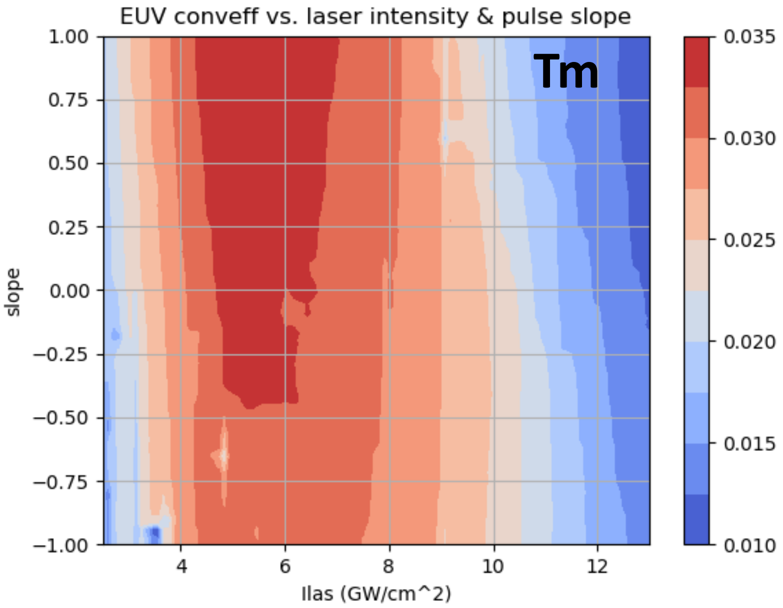
- (Ignore y-axis units.)

Tm heated tin disk and tin vapor targets have the same ~3.5% peak CE





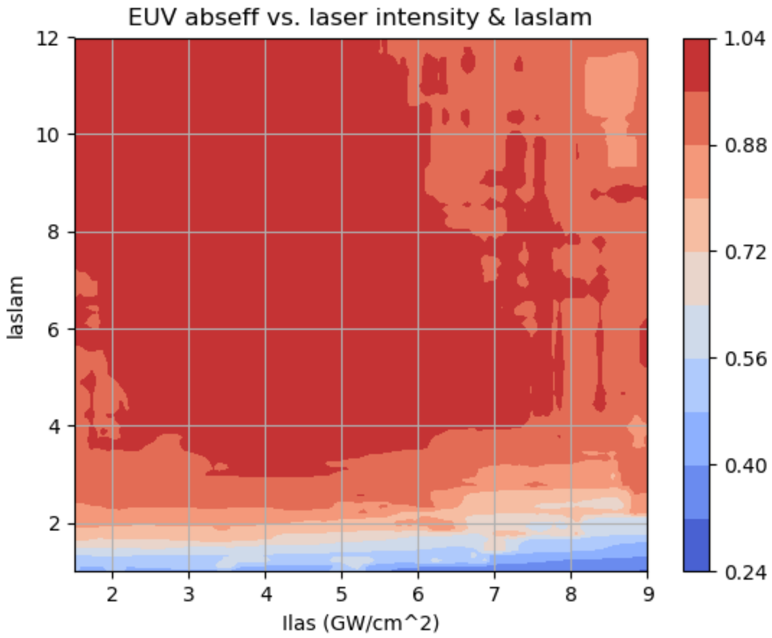
Tm Tin **vapor**



Tm Tin **disk**

- Ramping the laser intensity up during the pulse improves the CE for both disk and vapor.

Tin vapor targets have low laser absorption for a laser wavelength of less than ~3 μm



- The column mass (g/cm^2) is the same for all targets.
- The density is proportional to $1/\lambda^2$.
- The shock wave crosses the target much faster for short wavelength lasers and the target begins to decompress very early.
- A small fraction of the laser light is absorbed in the later part of the run for short wavelengths.

Conclusions

- The CE of liquid tin and tin vapor targets is similar when driven by CO_2 and Tm lasers.
- The flexible pulse shaping capability of Tm lasers can increase the CE.
- Simulations show a broad range of laser wavelengths that deliver similar conversion efficiency.
- The talk by Siders on Wednesday shows that thulium lasers have a much higher efficiency at turning electricity into laser light than current CO_2 lasers.
- Further investigation of Tm lasers is justified and HYDRA is ready to perform simulations that can speed the development process.